Experimental Investigations of He II Heat Transfer through a Short Section of LHC Inner Triplet Quadrupole Heat Exchanger

Ch. Darve, Y. Huang, T. H. Nicol and T. J. Peterson

***Abstract*—The LHC inner triplet quadrupoles, cooled by pressurized He II, are subjected to a total heat load of more than 7 W/m at nominal luminosity. The heat absorbed in pressurized He II will be transferred to the saturated, two-phase He II via a corrugated copper pipe. Experimental investigations of He II heat transfer across the corrugated pipe are reported. The test sample of corrugated pipe is filled with pressurized He II and with saturated He II on the outside. The maximum heat flux to the test sample is up to 145 W/m^2. The characteristics of the corrugated copper pipes under investigation are the Kapitza resistance, thermal conductivity of the material and the geometry of the pipe. The test results for a series of bath temperatures and surface treatments are included.**

***Index Terms*— Heat exchanger, He II, Kapitza, LHC**

I. Introduction

THE Large Hadron Collider (LHC), currently under construction at CERN, will produce two counter-rotating proton beams, each with an energy of 7 TeV for head on collisions at 4 points. As part of the US LHC Accelerator Project, Fermilab is contributing to the design and production of the inner triplet systems located at each of the four LHC interaction regions (IR).

The inner triplet quadrupoles will operate in a pressurized He II bath at 1.9 K in order to remove a 1.9 K heat load on the order of 200 W over 30 m. As a comparison, the typical 1.9 K heat load for a single arc cooling loop is approximately 40 W for 107 m. LHC IR inner triplet quadrupole cryostats will use two-phase He II as a cold source. A large diameter heat exchanger is installed between the saturated flow and the static pressurized He II. Geometrical and thermal constraints dictated a heat exchanger outside of and parallel to the cold mass. Magnet heat flows through pressurized He II to the heat exchanger and across the copper tube wall to saturated He II [1]. The resulting temperature rise is dominated by the Kapitza effect at the heat exchanger wall interface between the liquid and the solid.

In the framework of the LHC cooling scheme study, several test runs permitted us to investigate the performance of the heat exchanger. Hence, three 100 mm long samples have been tested at Fermilab in order to predict the total heat transfer coefficient for potential heat exchanger pipes. This material study is complementary to the main test for the validation of the inner triplet heat exchanger design and provides data for the analysis of a full-scale Heat Exchanger Test Unit which has been tested at CERN (IT-HXTU) [2].

II. Heat transfer model and test procedure

The LHC inner triplet cooling scheme is based on heat exchange between the pressurized He II bath and the flowing saturated He II [3]. The heat generated by dynamic particle beam effect in the superconducting magnets is transported by conduction in pressurized He II to the heat exchanger pipe. The actual design incorporates an oxygen free high conductivity (OFHC) copper pipe. A corrugated geometry provides an increase of the surface area by a factor 1.5 compared to a smooth tube.

The test sample is filled with pressurized He II, at temperature *Tpres*, while saturated He II, at temperature *Tsat*, surrounds its external wall. In spite of the reversed location of the pressurized and saturated He II location the heat transfer process is the same as in the actual inner triplet heat exchanger design.

The heat load, *Q*, generated by Joule-effect through an electrical resistance to the pressurized He II, creates a small difference of temperature, *Tpres-Tsat* across the copper wall, which is wetted on its surfaces over their full length. Thus, the total transverse thermal resistance, *Rth*, is equal to the sum of the two Kapitza resistances at the interface between solid and liquid, plus the resistance of the copper wall. Since the temperature difference at a constant bath temperature is negligible compared to this bath temperature, the thermal conductivity can be considered constant, hence, we assume that the given bulk thermal resistance of the copper is constant. We can make the assumption that both Kapitza resistances at the interface of the copper pipe with the pressurized and saturated He II, are equal to *RKapitza*. Thus, we can write:

$$Rth = \frac{Tpres - Tsat}{Q} = 2(RKapitza) + Rcu$$

Within the small variation of temperature observed, the Kapitza resistance varies as $Tsat^{-3}$. Therefore, we can express *Rth*, as follows:

$$Rth = a\left(\frac{1}{Tsat^3}\right) + b$$

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with:

$$a = \frac{2}{(CKapitza)S} \qquad\qquad b = \frac{th}{(\lambda cu)S}$$

where *Ckapitza* is the Kapitza coefficient characterizing the interface, th is the wall thickness, S the interface surface area and λcu is the copper thermal conductivity.

Thus, plotting *Rth* versus $Tsat^{-3}$, we can determine the Kapitza coefficient and the copper thermal conductivity. The transverse conductance is found from the intercept β. The Kapitza conductance is defined by the ratio *Q/D*T per unit area, where *DT* is the difference of temperature between the copper and the He II media. Hence, the Kapitza conductance, which has units, $W \cdot K^{-1} \cdot cm^{-2}$, is deduced from *Ckapitza*.

III. Description of the experiment

A. Samples

The small-scale samples are 100 mm long corrugated pipes. The design of the short sample device assembly is shown in Fig. 1. The assembly is designed in order to be tested in a 500 mm long and 500 mm ID dewar. Parameters of the three samples are defined in table I. The first tested sample is the same corrugated pipe used for the IT-HXTU. It is made out of industrial OFHC copper, without any specific surface treatment. The second tested sample is the same geometry as the previous one but treated with hydrochloric acid, then rinsed with distilled water. The third sample permits us to compare the effect of the material quality. For this reason, we have chosen a bronze (95% Cu-5% Sn) sample. The geometry of the last one is different from the two first samples. The shape of sample #1 and #2 is a helical corrugated pipe, in contrast to the bellows shape for sample #3.

The corrugated pipe was soldered into grooves of thick-wall lower thermal conductivity stainless steel flanges at both ends.

B. Test Set-up

The test setup is composed of the test dewar, pumping unit, vacuum pump, helium gas supply, and liquid helium supply.

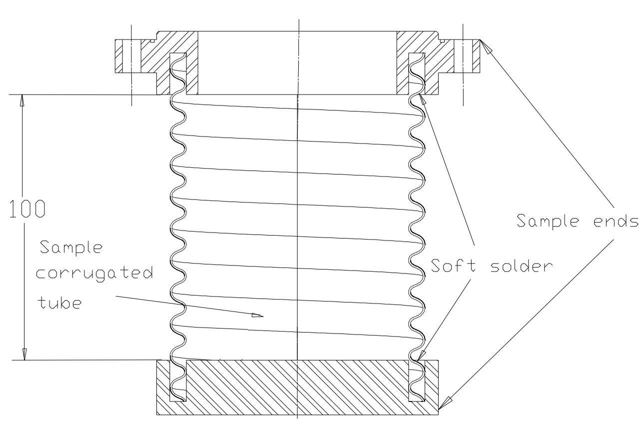

Fig. 1. Corrugated pipe testing device sample assembly

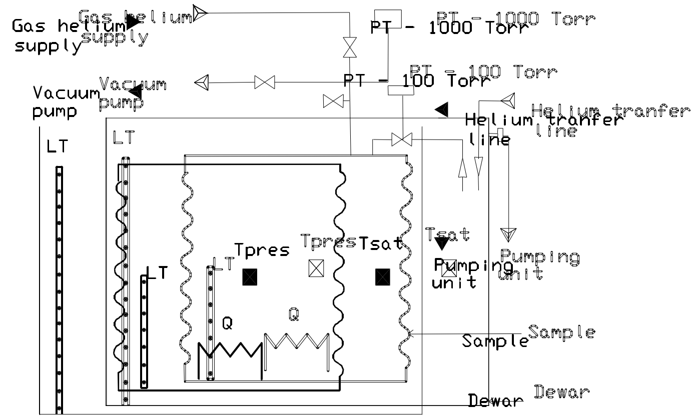

Fig. 2. Scheme of the cryogenic system

Several valves, indicators and sensors permit precise control of the measurements. Thermometer, level indicator, and pressure transducer are mounted in both saturated and pressurized He II volumes. Two calibrated Lake Shore® germanium thermometers measure the temperature of the pressurized, *Tpres*, and the saturated He II, *Tsat*. Both temperatures are deduced from their respective Chebychev calibration fits. The temperature is measured with the four-wire technique and the use of 0.2 μA current prevents self-heating. A resistive heater is mounted inside the test sample to provide a heat load, *Q*, to the pressurized He II bath. Fig. 2 illustrates the schematic of the test system.

The system minimizes parasitic leaks due to radiation, conduction, and heat transport into superfluid helium. An electrical rack contains power supplies for the instrumentation and control as well as switches from the electronics. The signals are read through digital voltmeters (DVM). The two DVMs communicate the read-out voltages to a computer. The data acquisition system permits the recording of five sets of data per minute. Each set of data consists of ten channels.

C. Test Procedure

The test mainly consists of measuring the steady-state behavior of the heat exchanger corrugated pipe, such as temperature difference *Tpres-Tsat*, for various applied heat loads, *Q*, and various temperatures *Tsat*. This temperature difference provides the total thermal resistance. The heat loads are applied to the pressurized sample inner volume, acting as a dummy magnet. LHC magnet heat load values are scaled down to this small scale. Therefore, the input power ranged from 0 to 9 Watts. The saturated He II temperature, can be controlled by the opening of a valve to the pumping unit. During the measurement, the helium level indicators confirm that 100% of the sample length is wetted on both sides. Therefore, measurements are provided for a corrugated pipe, wetted over 100% of its perimeter by the liquid phase of the saturated He II.

Once the saturated He II temperature is stabilized, the electrical power is increased in the pressurized He II volume in steps. For each heat load, temperatures are recorded after temperatures are stabilized within 1 mK.

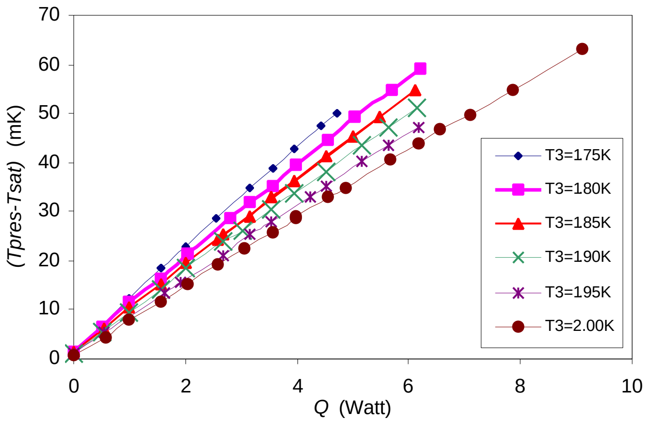

Fig. 3. Measured temperature differences for sample #1

Finally, measurements are repeated for temperature, *Tsat*, varying from 1.75 K to 2.00 K with an increment of 0.05 K. The run was repeated for each sample assembly.

IV. Results and Discussion

A. Results

The difference of temperature between the saturated and the pressurized He II is investigated for different temperatures *Tsat* expected during the LHC run. The maximal difference of temperature expected during the LHC operation is estimated to be 50 mK when the saturated vapor temperature at the feedbox on the pumping line is equal to 1.85 K [1].

The difference of temperature, *Tpres-Tsat*, is measured as a function of the applied heat load, *Q*. For each sample and for various saturated He II temperatures, we can plot the evolution of *Tpres-Tsat* versus *Q*. Fig. 3 and Fig. 4 focus on the untreated OFHC sample #1, which is similar to the material used for the IT-HXTU and for the current inner triplet design. Fig. 3 shows a typical set of raw measurements. The measurements display linear behavior. Test run analyses for the two other samples are consistent with Fig. 3.

In a second step, we plot *Rth* vs. $Tsat^{-3}$ for each sample. Fig. 4 illustrates the linear behavior of the transverse thermal resistance vs. $Tsat^{-3}$. Results for the two other test runs are consistent with this observation. Hence, we can deduce the Kapitza coefficient and the thermal conductivity of the three samples by using the linear regression fits to these curves.

The transverse thermal resistance expressed for sample #1 yields a *CKapitza*, equal to $893 \pm 27\ \mathrm{W \cdot m^{-2} \cdot K^{-4}}$. The copper thermal conductivity is of the order of $88\ \mathrm{W \cdot K^{-1} \cdot m^{-1}}$. The Kapitza conductance at 1.85 K is $0.565\ \mathrm{W \cdot K^{-1} \cdot cm^{-2}}$.

Fig. 5 compares performances of the three samples. The total resistance, *Rth*, is illustrated vs. $Tsat^{-3}$. Table I summarizes results for each sample. Sample #2 shows Kapitza conductance of $0.720\ \mathrm{W \cdot K^{-1} \cdot cm^{-2}}$.

Some parasitic heat is transferred to the system by radiation, conduction through the supporting system and the conduction in He II. Calculation and experimental data predict 0.2 Watt of parasitic heat to the system. The error in the measurement of the temperature difference is ± 1 mK for the observed temperature range. The root-mean-square error of the two germanium temperature sensors calibration is 0.71 mK and the accuracy is 3 mK. The error in the Kapitza coefficient calculation is estimated to ± 3 %.

B. Discussion

Test results emphasize that the Kapitza conductance depends strongly on the material quality and the surface treatment. For thin OFHC copper the Kapitza effect is the dominant resistance to heat transfer over conduction for OFHC materials. With respect to the temperature range explored, the influence of the treated surface permits a heat exchange improvement of 27% for OFHC copper.

The performance of sample #3 compared to sample #1 is 37% lower. Whereas, the conduction is negligible compared to the interfacial Kapitza phenomenon in the case of sample #1 and #2, conduction through the solid is not negligible for the case of sample #3. Conduction through the solid is strongly dependent on parameters like material quality.

The measured thermal conductivity of the OFHC copper sample agrees well with values found in the literature. It corresponds to an OFHC copper with a RRR of 50. Measurements show a thermal conductivity at 2 K about 37 times larger for OFHC samples than for the bronze material.

Test results show that measured Kapitza conductances are in good agreement with results from other experiments [4]. If we compare these results to those obtained for a smooth pipe [5], we note that similar Kapitza coefficients are obtained in the case of OFHC samples.

Whereas this experimental material study proves the good thermal performance of an OFHC corrugated heat exchanger with a treated surface, the choice of the final heat exchanger for the LHC inner triplet must consider additional issues, such as the difficulty of chemical treatment applied on a full-scale unit. The cost and complexity of a large-scale treatment on the corrugated pipe would be important. For example, a nitrogen atmosphere could prevent the oxidation of the treated copper pipe. Due to the good performance of the OFHC sample #1 and the reasonable cost of this material for the full production of the LHC inner triplet heat exchanger, there is no need to choose a different material and surface

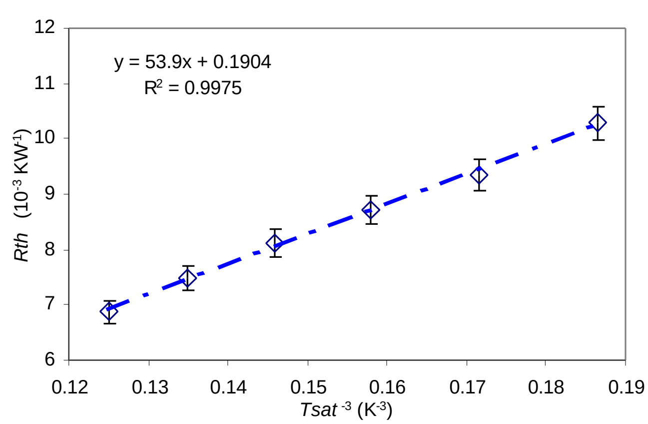

Fig. 4. Total transverse thermal resistance for sample #1

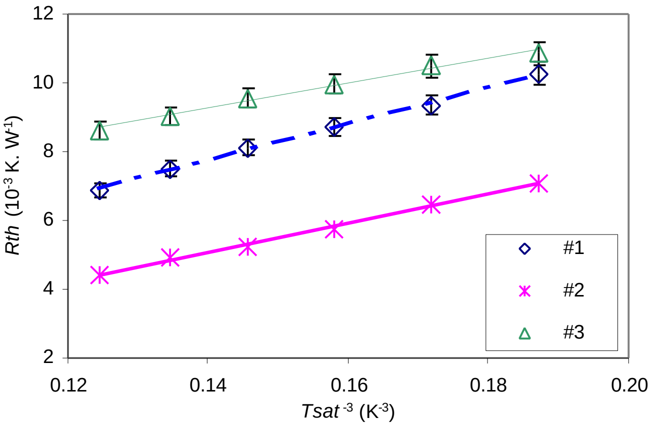

Fig. 5. Comparison of thermal resistance

treatment than the existing one. The current choice of the heat exchanger design can be partly validated with this test run. It will be confirmed by the results of the inner triplet Heat Exchanger Test Unit.

The IT-HXTU will allow us to investigate the thermo-hydraulic behavior and thermal performance of the inner triplet heat exchanger, taking into account the saturated He II mass-flow estimate for LHC conditions as well as the actual wetted surface area.

V. CONCLUSIONS

The primary goals, measurements of the heat exchanger performance and the temperature difference across the small-scale LHC inner triplet heat exchanger wall, was successful and permits extrapolation to the full-scale model (IT-HXTU). The measured total thermal conductance yields a Kapitza coefficient of 893 $W \cdot K^{-4} \cdot m^{-2}$ $\pm 3\%$. Therefore, a Kapitza conductance of 0.565 $W \cdot K^{-1} \cdot cm^{-2}$ is estimated for the operating temperature of 1.85 K.

On the other hand, measurements were dedicated to material studies and thermal performance of copper based corrugated pipes, at He II temperature. We came to the conclusion that an improvement of 27% of the heat transfer performance can be achieved if the surface of an OFHC corrugated pipe is treated with hydrochloric acid.

The results of the test eliminate the choice of a bronze bellows, with performance 37% lower than the untreated OFHC choice.

Even if we measured better performance for treated OFHC corrugated pipe, the choice of the LHC IRQ inner triplet heat exchanger material should be compatible with any method of surface treatment. Since the measured performance of the existing heat exchanger is favorable, there is no need for further improvement. The final validation will be given with the IT-HXTU results.

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TABLE I : CHARACTERISTICS OF THE THREE SAMPLES AND RESULTS

	#1 - OFHC	#2 – OFHC + HCl	#3 - Bronze
Characteristics			
OD/ ID (mm)	97/86	97/86	123/101
Wall thickness (mm)	0.7	0.7	0.5
Corrugation depth (mm)	5	5	11
Corrugation pitch (mm)	12.4	12.4	11.7
Surface (cm^2) for one side	416	416	978
Shape of the corrugated pipe	Helical	Helical	Bellows
Surface treatment	None	Hydrochloric acid	None
Results			
CKapitza ($W \cdot K^{-4} \cdot m^{-2}$)	893	1138	565
Kapitza conductance @ 1.85 K ($W \cdot K^{-1} \cdot cm^{-2}$)	0.565	0.72	0.357
Thermal conductivity @ 1.85 K ($W \cdot K^{-1} \cdot m^{-1}$)	88	88	2.4
Relative performance	Ref.	27%	-37%